Geomorphology 321 (2018) 117–128

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

An assessment of landform composition and functioning with the first proglacial systems dataset of the central European Alps

Jonathan L. Carrivick [a,*], Tobias Heckmann [b], Andy Turner [a], Mauro Fischer [c]

[a] School of Geography, University of Leeds, Woodhouse Lane, Leeds, West Yorkshire LS2 9JT, UK
[b] Physical Geography, Catholic University of Eichstaett-Ingolstadt, Germany
[c] Institute of Geography, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland

ARTICLE INFO

Article history:
Received 18 June 2018
Received in revised form 20 August 2018
Accepted 21 August 2018
Available online 23 August 2018

Keywords:
Proglacial
Glacier
Landform
Meltwater
Landscape evolution
Hillslope
Fluvial

ABSTRACT

Proglacial systems are enlarging as glacier masses decline. They are in a transitory state from glacier-dominated to hillslope and fluvially-dominated geomorphological processes. They are a very important meltwater, sediment and solute source. This study makes the first quantitative, systematic and regional assessment of landform composition and functioning within proglacial systems that have developed in the short term since the Little Ice Age (LIA). Proglacial system extent was thus defined as the area between the LIA moraine ridges and the contemporary glacier. We achieved this assessment via a series of topographic analyses of 10 m resolution digital elevation models (DEMs) covering the central European Alps, specifically of Austria and Switzerland. Across the 2812 proglacial systems that have a combined area of 933 km^2, the mean proportional area of each proglacial system that is directly affected by glacial meltwater is 37%. However, there are examples where there is no glacial meltwater influence whatsoever due to complete disappearance of glaciers since the LIA, and there are examples where >90% of the proglacial area is probably affected by glacial meltwater. In all of the major drainage basins; the Inn, Drava, Venetian Coast, Po, Rhine, Rhone and Danube, the proportions of the combined land area belonging to each landform class is remarkably similar, with >10% fluvial, ~35% alluvial and debris fans, ~50% moraine ridges and talus/scree, and ~10% bedrock, which will be very helpful for considering estimates of regional sediment yield and denudation rates. We find groupings of the relationship between proglacial system hypsometric index and lithology, and of a slope threshold discriminating between hillslope and fluvial-dominated terrain, both of which we interpret to be due to grain size. We estimate of contemporary total volume loss from all of these proglacial systems of 44 M m^{3}a^{-1}, which equates to a mean of 0.3 mm·a^{-1} contemporary surface lowering. Overall, these first quantifications of proglacial landform and landscape evolution will be an important basis for inter- and intra-catchment considerations of climate change effects on proglacial systems such as land stability, and changing water, sediment and solute source fluxes. Our datasets are made freely available.

1. Introduction

Proglacial systems are amongst the most rapidly changing landscapes on Earth. They are progressively increasing in areal extent, and arguably also in instability due to ongoing effects of climate change on glaciers, permafrost and consequent hillslope and fluvial processes (Ballantyne, 2002; Carrivick and Heckmann, 2017). They are a source of water, sediment, solutes (WSS) and hazardous geophysical phenomena, particularly landslides and glacier outburst floods (GLOFs) (e.g. Carrivick and Tweed, 2013, 2016). WSS fluxes dictate alpine hillslope and river channel stability, water thermal and chemical regime, biological communities (fish, invertebrates, plants, algae), and ecosystem functions that influence water quality (nutrient and carbon cycling). Proglacial system geomorphological composition and functioning and landscape evolution are therefore of great importance for natural environmental systems and for human activity. Furthermore, alpine proglacial systems in both the European Alps and globally have influence on human and natural systems far beyond the alpine zone. For example, there are 14 million people living in the European alpine arc (Litschauer, 2014) and there are several billion people directly dependent on water from alpine rivers globally. Across Europe, alpine river tributaries contribute up to eight times the water discharge that might be expected given their basin size and thus have been termed the 'water towers of Europe' (EEA, 2009; Huss, 2011).

Proglacial systems are transitioning from being dominated by glacial processes to being more influenced by paraglacial hillslope and fluvial processes (Church and Ryder, 1972; Ballantyne, 2002; Carrivick and Heckmann, 2017). A transitory state implies intense hydrological, geomorphological and ecological dynamics (c.f. Micheletti and Lane, 2016; Delaney et al., 2018; Heckmann and Morche, in press). However,

* Corresponding author.
E-mail addresses: j.l.carrivick@leeds.ac.uk (J.L. Carrivick), mauro.fischer@giub.unibe.ch (M. Fischer).

https://doi.org/10.1016/j.geomorph.2018.08.030
0169-555X/

identifying WSS patterns due to these environmental transition(s) is not straight-forward due to spatio-temporal variability and non-linear and stochastic relationships (Bennett et al., 2014). Furthermore, whilst paraglacial activity is generally considered as a set of earth surface processes that are dominant during the transition time period (Carrivick and Heckmann, 2017), changes in hillslope and channel composition or landforms and sediments, and functioning such as connectivity, can alter the relative importance of these hillslope and fluvial processes in space and time (Bennett et al., 2014; Lane et al., 2017).

Despite the importance of understanding WSS production, pathways and effluxes, studies of geomorphological composition and functioning within proglacial systems have been few and spatio-temporally disparate. Indeed, geomorphological mapping within proglacial systems tends to be conducted either as a basis for field monitoring of water and sediment fluxes (e.g. Beylich et al., 2017), or as a preliminary step towards making targeted close-range field surveys of topographic changes (e.g. Carrivick et al., 2013; Kociuba, 2017). There have been no quantitative efforts to evaluate the geomorphological composition of proglacial systems across a region, nor to evaluate spatial coverage of major geomorphological processes across a mountain range scale region, nor to evaluate likely sediment sources, pathways and sinks within proglacial systems across a region. These three efforts are necessary precursors to regionalising or upscaling field measurements, and more specifically for making quantitative estimates of volume and mass changes within (and exports from) proglacial systems.

This study therefore aims to make the first comprehensive quantitative, systematic and regional assessment of landform composition and functioning within proglacial systems. We focus on the central European Alps region due to that region having readily-available data and because we have (published) knowledge of some of the catchments in that region, but we advocate the relevance of this work globally.

2. Study areas, datasets and methods

2.1. Proglacial zone definition

Proglacial systems across the central European Alps analysed in this study are situated in both Austria and Switzerland due to both of those countries having high-resolution (10 m grid cell size or less) seamless digital data availability. Austria glacier outlines for both the Little Ice Age (LIA) and for the contemporary situation were obtained from A. Fischer et al. (2015), Groß and Patzelt (2015) and Glaziologie Österreich (2016). A 10 m grid cell size DEM of Austria that had been down-sampled from airborne laser scanner (ALS) data was obtained via Daten Österreichs (2016).

Swiss glacier outlines for both the LIA considered those of Maisch (2000). For the contemporary (year 2010) situation they were obtained by manual digitization of high-resolution (0.25 m) aerial orthophotographs acquired between 2008 and 2011 (M. Fischer et al., 2014, 2015). High-resolution topographic data for Switzerland comprising a 2 m grid cell size, down-sampled to 10 m grid cell size for this study to be comparable to the Austria Digital Elevation Model (DEM), was derived from Airborne Laser Scanning (ALS) as published by M. Fischer et al. (2014, 2015).

Proglacial systems across the central European Alps (Fig. 1) were defined automatically by subtracting modern glacier outlines from LIA glacier outlines after Carrivick et al. (accepted). This simple calculation produced a proglacial system extent or boundary, which is necessary for spatial analyses, and a system area (spatial size). In order to minimise misidentifications and extraneous parts of proglacial systems (such as where: (i) some glaciers have reduced in width at relatively high elevations; (ii) some glaciers have reduced in ice extent on plateaux or on cols as a result of fragmentation or disintegration; and, (iii) portions of the landscape presently in transition between ice-marginal and proglacial regimes), we specified a 100 m buffer around the modern outlines and excluded this area from our analyses.

Geological data was sourced from the International Geological Map of Europe (Asch, 2003; IGME, 2016) and chosen over national level datasets so as to give consistency in mapping and terminology as well as a general-level classification suitable for the regional-scale analysis of this paper.

With consideration of future use of our results for understanding WSS fluxes from proglacial systems and especially of those transmitted downstream where they affect local populations, hydropower and communications infrastructure, and agriculture we discriminate by major central European drainage basin. These outlines (watersheds) were sourced from the Global Runoff Data Centre (GRDC) www.grdc.de.

2.2. Spatial discrimination of major geomorphological process domains

In a first-order classification of proglacial systems based on their topography, we not only calculated statistics of elevations (Fig. 2A) and slopes (Fig. 2B) of all grid cells within each proglacial system, but also the hypsometric index of each as categorised following the Jiskoot et al. (2009) approach where very top heavy hypsometric values indicate much more area at high elevation than at low, and very bottom heavy hypsometric values indicate much more area at low elevation than at high.

Our spatial discrimination of major geomorphological process domains was achieved in four workflow stages, and was in terms of

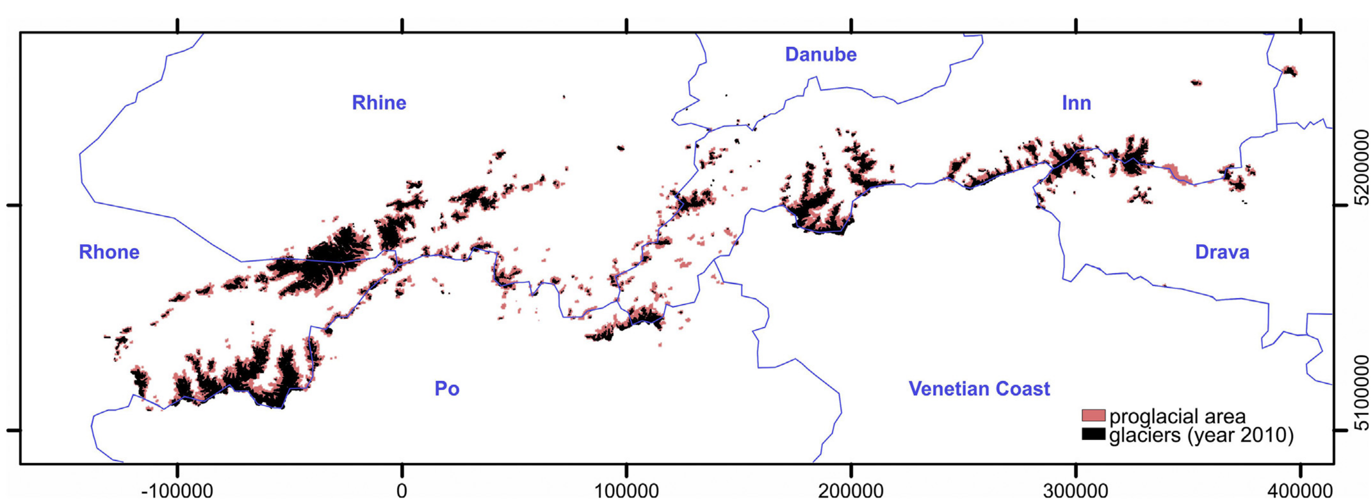

Fig. 1. Spatial coverage of glaciers and proglacial systems across central Europe (Austria and Switzerland) with major drainage basin boundaries (watersheds). Grid coordinates (metres) are projected in UTM zone 33N.

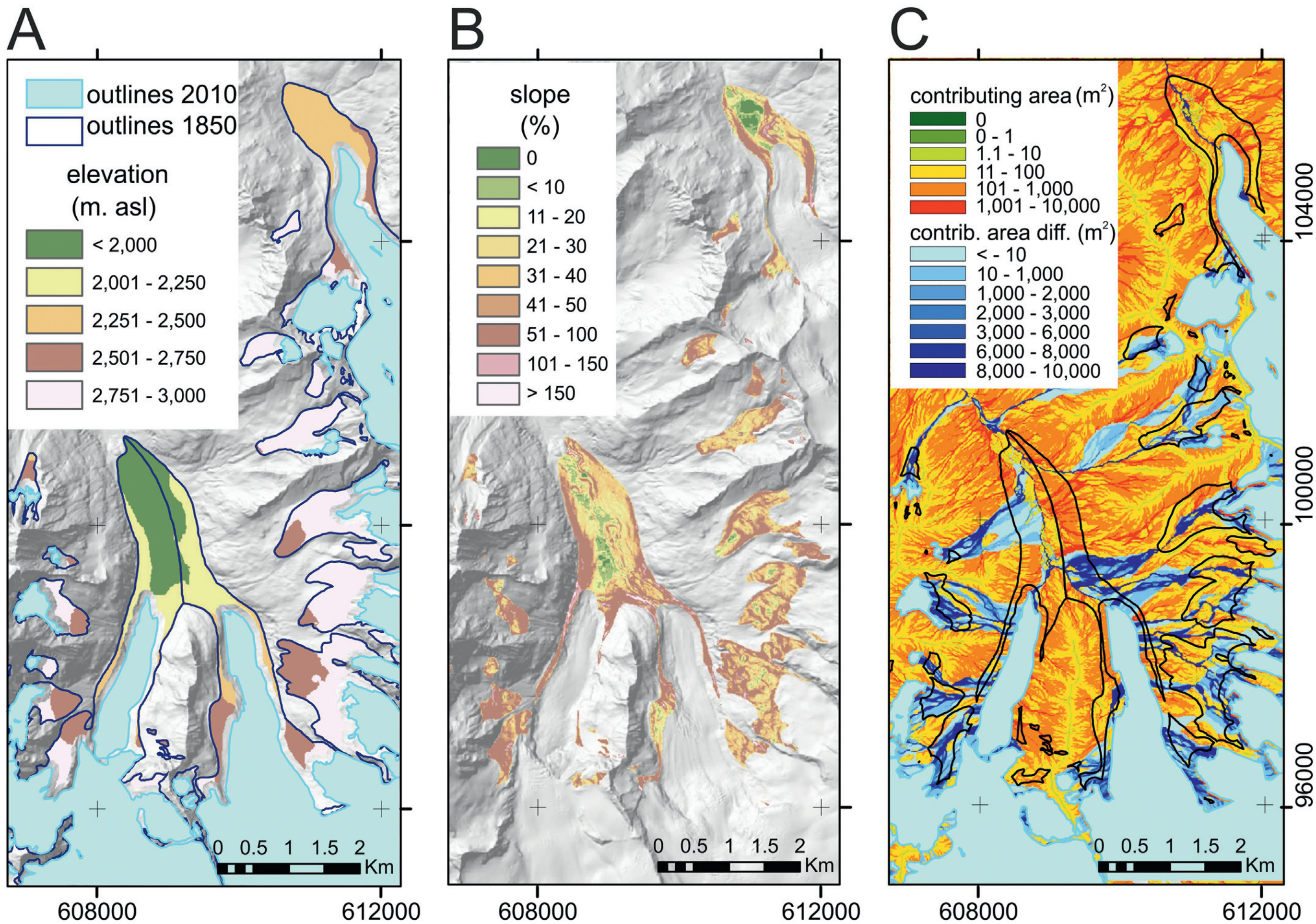

Fig. 2. Example of the spatial discrimination of proglacial systems using glacier outlines from the LIA 'year 1850' (Maisch, 2000) and from the present 'year 2010' (A), of categories of slope in these systems (B) and of contributing area analysis (C), in this case for the Glacier du Mont Miné and Glacier de Ferpécle area in Switzerland. Shades of blue in panel 1C can be considered to represent a 'likelihood' of that grid cell receiving glacial meltwater runoff, being calculated per grid cell as the difference between grids of contributing area with and without glaciers. Grid coordinates are projected in CH1903_LV03.

grid cells that are either predominantly influenced by glacier meltwater, other fluvial (fluid flow) processes, or grid cells that are dominated by hillslope (mostly gravitational) processes.

Firstly, slope grids (Fig. 2B) were computed and the cell values extracted for each proglacial zone. Secondly, contributing area was determined per grid cell via the D-Infinity flow direction and contributing area algorithms (Tarboton, 1997), as available in the TauDEM (2016) set of tools. These algorithms were chosen to recognise the likelihood of braided river networks in proglacial systems where local slopes are shallow. Contributing area calculations assume that (runoff) contributing area correlates with water discharge. Thus they are not valid for grid cells that might receive runoff from a glacier where discharge is driven by melt and often with significant temporary storage. We therefore differenced grids of contributing area with and without glacier surfaces in them. This calculation discriminated grid cells that cannot receive runoff from glaciers, as coloured greens and reds in Fig. 2C, versus grid cells that probably do receive runoff from glaciers, as coloured shades of blue in Fig. 2C. This calculation of the spatial influence of glacial meltwater runoff does not consider flood inundation extent, and we realise flooding is a regular phenomenon in proglacial systems, nor (non-glacial) valley side tributaries.

After excluding all glacier-meltwater influenced grid cells, we thirdly fitted a polynomial curve with varying numbers of parameters i.e. those of the form:

$$Y = a^*\left(X^2\right) + b^*(X) + c \tag{1}$$

where Y = log contributing area, and X = log slope, was fitted to the scatterplot of points of log slope – log contributing area for each proglacial zone using an algorithm provided in the Apache Commons Math library (https://commons.apache.org/proper/commons-math/userguide/fitting.html). For proglacial systems with >10 data points and for fitted curves with an identifiable maximum value, the corresponding log slope (X) value was extracted. The automated implementation of this model was via bespoke Java programs which we have made open source and for which we utilised some third party open source libraries as available via: https://github.com/agdturner/FluvioGlacial.

Fourthly and finally, conversion of this log percent slope to a degrees slope enabled mapping and calculation of the percentage area of each proglacial zone that is apparently dominated by either fluvial or hillslope processes.

The percentage area of each proglacial zone dominated by glacial meltwater was calculated similarly, by converting the difference in contributing area (Fig. 2C) to a binary 1 = difference, 0 = no difference, then summing the number of grid cells with a difference and calculating the area of these as a proportion of the total proglacial zone area.

2.3. Segmentation of major landform types

In order to estimate the proportion of different landform types associated with different geomorphological processes, we analysed the probability density function (PDF) of slope as described by Loye et al.

(2009). The method assumes slope to be normally distributed on characteristic landform types, and aims at decomposing the observed slope PDF into a user-specified number of normal distributions. The intersections of the resulting PDFs can then be used to discriminate the pertaining landform types. Unlike Loye et al. (2009), we applied the expectation-maximisation algorithm implemented in the R package mixtools (Benaglia et al., 2009; Heckmann et al., 2016a, 2016b) to the slope PDF of a sample (n = 25,000). We limited this sample to a subarea of the countrywide DEM10, namely to the area covering the proglacial systems plus a 200 m buffer to include adjacent rockwalls, and with glacier-covered areas masked.

Fig. 3A illustrates that the PDFs inferred from the 30 samples are more and more consistent with increasing mode; the largest scatter is evident for the "floodplain" class, whilst the PDFs representing rockwalls are all very similar. Accordingly, the range of possible intersections of the single landform type PDFs is wider for T1 and T2, and quite narrow for T3. Depending on the alpine morphotectonic unit, Loye et al. (2009) reported T3 in the range 46° to 54°; intersections at T1 and T2 were not explicitly reported (due to the focus of the paper), but can be extracted from their diagrams: T1 = 8° to 13°, T2 = 21° to 26°. Note that Loye et al. (2009) used a one metre cell size DEM, so the values of slope are expected to be higher than those computed from our ten metre cell size DEM.

In order to validate the choice of intersections between each probabilistic group of slope values, we analysed a 10 m cell size DEM of part of the Val d'Hérens (Switzerland), for which Lambiel et al. (2016) have published a digital geomorphological map. We used the polygons of selected landform types to extract the associated PDFs of slope from the DEM (Fig. 3B) and we found that the total slope PDF of the Val d'Hérens (thick black curve in Fig. 3B) was representative of the slope PDF of proglacial systems that we investigated in the Austrian and Swiss DEMs.

Regarding the intersections of slope PDFs of different landform types, T3 appears to be consistent with the intersections of the rockwall PDF with the PDFs of "talus" and "moraine". The slope PDF of "fluvial deposits" in the map is multimodal, probably accounting for floodplains, terraces and alluvial cones of different gradient; therefore, two normal distributions have been fitted visually (the blue and green dashed curves) to the first two modes of the "fluvial deposits" PDF. They intersect with each other in the range of T1 (upper panel), and with the "talus" PDF in the range of T2. Based on these observations, we regard our classification as sufficient and set the intersections for discriminating probabilistic slope groups at (a) 7.5°, (b) 18° and (c) 42°.

In order to assess the uncertainty of the intersection values due to sampling and iterative PDF decomposition, we repeated the PDF 30 times. We selected k = 4 as the user-specified number of single PDFs, assuming (intuitively) that the following landform types were most representative for proglacial systems: (a) rock walls, (b) steep slopes such as scree and lateral moraines, (c) alluvial or debris cones, and (d) floodplains. We assume that these landform types have markedly different PDFs of slope, and set the following initial means, μ, and standard deviations, σ, for the iterative normalmixEM algorithm, based on preliminary analyses of proglacial systems that we are especially familiar with, i.e. Ödenwinkelkees: Carrivick et al. (2013, 2015), and Kaunertal: Heckmann et al. (2016b) as (a) $\mu = 45°$, $\sigma = 3$; (b) $\mu = 30°$, $\sigma = 6$; (c) $\mu = 15°$, $\sigma = 7$; (d) $\mu = 5°$, $\sigma = 12$. Moreover, k = 4 is consistent with Loye et al. (2009).

2.4. Regional relationships of proglacial hypsometry and slope

One way analysis of variance (ANOVA) was used to analyse relationships between slope threshold (between hillslope-dominated and fluvially-dominated land, derived from slope-area analysis) with the categorical variables of hypsometric index and lithology. Hypsometric index was also employed as a quantitative variable to compare it in the same manner to lithology. Categories of lithology with <10 samples in them (sandstone, amphibolite, carbonates, meat-sediment group, marble, tonalite, sand, claystone) were excluded from the analysis for being not statistically significant. A test for equal variances was performed to identify 95% confidence intervals for the samples within each category. For each of these three relationships statistical groups were identified using Fischer's individual error rate.

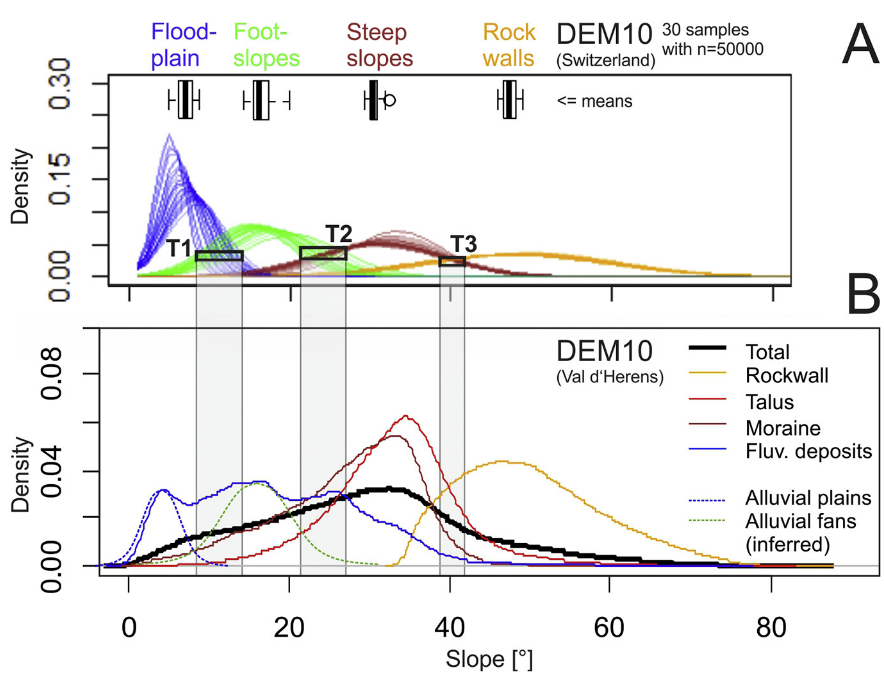

Fig. 3. A: Normal distributions of slope for four landform types generated from 30 samples of the Swiss DEM (glaciers and areas outside of proglacial areas + 200 m buffer excluded) after Loye et al. (2009, see text for details). The ranges where PDFs intersect are denoted T1 (flood plain ⇔ footslopes), T2 (footslopes ⇔ steep slopes) and T3 (steep slopes ⇔ rock walls). Boxplots show the distribution of corresponding means. B: The intersections of the empirical slope distributions of four landform types of the geomorphological map of Val d'Hérens (Lambiel et al., 2016) are fairly consistent with the ranges T1–T3 indicated in (A). See text for details.

Table 1
Selected statistics on the number, size and elevation distribution of 2812 proglacial systems across central Europe.

	Inn	Drava	V.Coast	Po	Rhine	Rhone	Danube
Number of proglacial systems	652	117	12	317	794	906	14
Area sum (km^2)	307.6	78.8	6.3	78.3	200.2	255.9	6.4
Elevation min. (m·asl)		1726	2209	1798			1902
Elevation max. (m·asl)	3974	3696	3357	3989	4040	4380	3276
Elevation mean (m·asl)	2679	2659	2709	2763	2581	2854	2411
Very top heavy (%)	0	0	0	0	<1	<1	0
Top heavy (%)	0	0	0	0	0	<1	0
Equidimensional (%)	49	25	42	96	96	94	36
Bottom heavy (%)	10	17	8	4	3	6	7
Very bottom heavy (%)	41	58	58	0	1	<1	57
Mean meltwater spatial influence (%)	40	48	46	16	29	29	47

Our proglacial system outlines and distributed elevation and meltwater influence are made freely available (Carrivick, 2018). The outlines are a shapefile in UTM zone 33N projection and with attributes of drainage basin, HI and percent meltwater influence per system. Distributed elevation enables slope and hence landform classes to be computed quickly as described above in this paper. The meltwater influence grid has been extracted/clipped to proglacial system extent but was computed using a regional DEM. Note that contributing area also requires the regional DEM to be analysed.

3. Results

In total we analysed 2812 proglacial systems (Austria: 23%, Switzerland: 77%) with a combined area of 933.5 km^2 (Table 1). These proglacial systems span a wide geographical area, several climatic and geological regions and a large elevation range. They have hypsometry that is predominantly equidimensional; i.e. a near-equal distribution of area at all elevations (e.g. in the Po, Rhine and Rhone drainage basins), whilst more than half of the proglacial systems within the Drava, Venetian Coast and Danube drainage basins are very bottom heavy, i.e. with much more area situated at lower elevations (Table 1).

3.1. Definition of spatial importance of glacial meltwater

Our spatially-distributed estimate of glacial meltwater influence agrees very well with reality, for example as shown in Fig. 4 for the Ödenwinkelkees catchment (Carrivick et al., 2013, 2015), where glacier-fed, glacier-influenced and groundwater streams create a distinguishable patchwork of (well-studied) streams and rivers (Dickson et al., 2012; Brown et al., 2015).

Across all of the central European Alps proglacial systems the mean proportional area of proglacial systems that is probably affected by glacial meltwater is 37%. However, there is a very wide dispersion to this data (Fig. 5) and we found no relationship between proglacial area size and percentage meltwater influence. Excluding the numerous examples of proglacial systems that apparently have no glacial meltwater influence, most obviously due to complete disappearance of glaciers from these catchments, there is a very large inter-quartile range (IQR) for proglacial systems within the seven drainage basins; specifically from and IQR of 19% (Po) to 55% (Rhone). The meltwater coverage histogram in Fig. 5 for the Inn drainage basin is normally distributed (excluding zeros), whereas those for the Po, Rhine, Rhone are skewed towards lower meltwater coverages, with modal values of ~5, 15 and 25%, respectively. The Drava, Venetian Coast and Danube basins have too few proglacial systems for a normality test to be significant. There are a few examples in both countries where virtually the entire area of a proglacial system is probably affected by glacial meltwater.

3.2. Geomorphological functioning: hillslope versus fluvial processes

The slope threshold determined from our slope-area analysis for separating fluvially-dominated and hillslope-dominated (mostly gravitational processes) grid cells for each proglacial system had a mean of 27° across the central European Alps. There is no statistically significant difference between the mean slope threshold values for each drainage basin (Table 2) at the 5% significance level. Slope threshold value histograms for proglacial systems within each of the seven major drainage basins are almost normally-distributed, with the mean and median values very similar (Table 2), although the Venetian Coast and Danube datasets that are too small in number (samples) for any significant distribution to be detected (Fig. 6; Table 2).

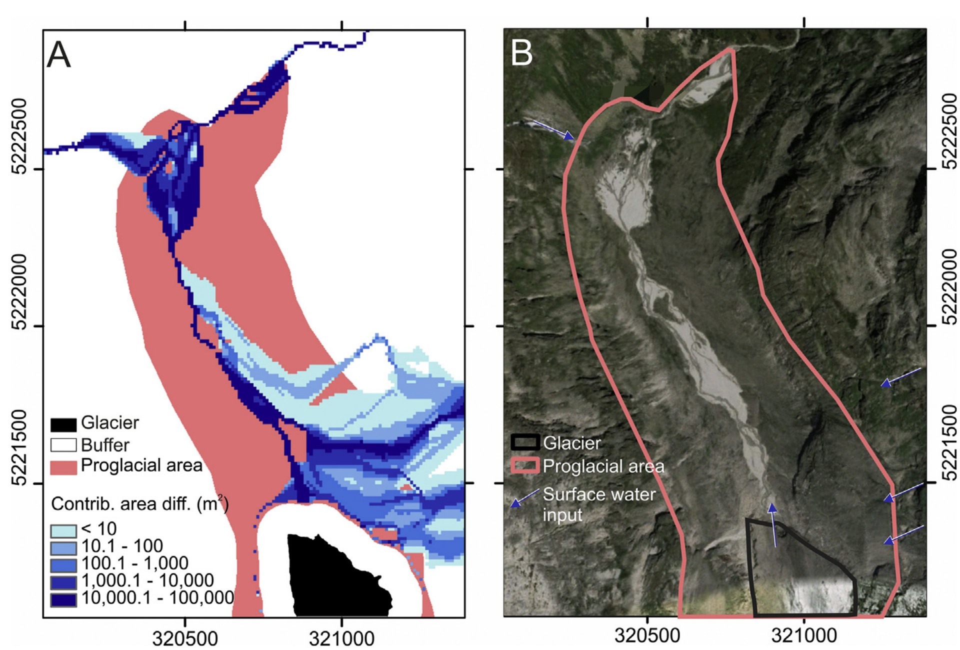

Fig. 4. Visual comparison of our contributing area-derived estimate of the spatial coverage and importance of glacier meltwater (A), versus reality (B), as for the Ödenwinkelkees catchment in central Austria, where surface water inputs are from Dickson et al. (2012) and Brown et al. (2015).

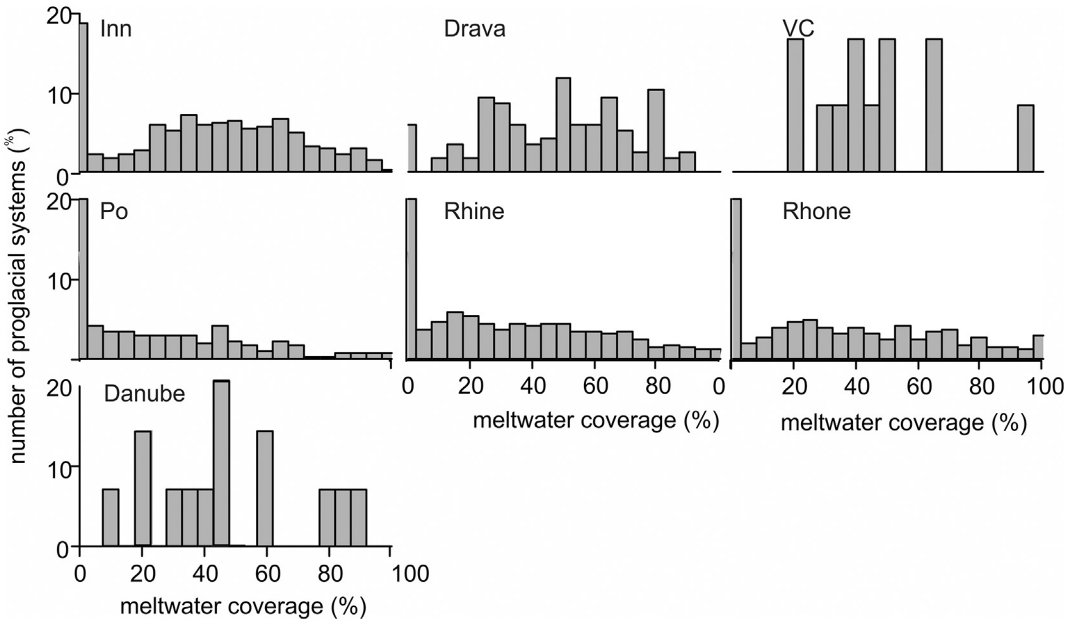

Fig. 5. Histograms of meltwater coverage (% of total proglacial system area) for each major drainage basin with headwaters in the central European Alps.

Analysing the slope threshold for each proglacial zone permitted calculation of the area of each proglacial zone that is predominantly affected by fluvial or by hillslope activity. Overall, 35% of proglacial systems across the central European Alps have >90% of their area dominated by hillslope activity and just <10% of their area dominated by fluvial activity. There is wide dispersion in this data and we found no difference in the histograms of the percentage area coverage of hillslope activity between major drainage basins. Fig. 7A is an example of mapping out grid cells per proglacial zone coloured by whether their slope is above or below the slope threshold for that proglacial zone. This map hints at the similar total spatial coverage of each of the two major process domains. Notwithstanding that many individual systems are hillslope activity-dominated, as mentioned above. The total area that is predominantly controlled by fluvial processes is ~472 km^2 and the total area corresponding to dominant hillslope processes is ~453 km^2; i.e. in terms of total proglacial system land area across the central European Alps there is a 50/50 split between fluvial and hillslope dominance.

3.3. Geomorphological composition

Our slope-based geomorphological classification agrees well visually with reality as measured either from our own experience (Ödenwinkelkees: Carrivick et al., 2013, 2015; Kaunertal: Heckmann et al., 2016a, 2016b) or from published geomorphological maps such as that by Lambiel et al. (2016) for the Val d'Herens (Fig. 8). We attempted a quantitative measurement of the 'goodness of agreement' in these Fig. 8 maps but that was hampered by differences in the mapping, such as Lambiel et al. (2016) did not map rock walls. Fig. 7B maps out grid cells coloured by which landform class they belong to, as discriminated by the PDF analysis. This is essentially a rudimentary automated geomorphological mapping with advantages over expert judgement-driven mapping of being fast, repeatable and easily applied across multiple sites and large (mountain range) scales simultaneously. The proportions of the combined proglacial system area belonging to each landform class is remarkably similar between each of the seven major drainage basins, with >5% fluvial, ~35% fans, ~50% moraine ridges and talus/scree, and ~10% bedrock (Fig. 7C).

Table 2
Selected descriptive statistics of the slope threshold (degrees) for discriminating between hillslope-dominated and fluvially-dominated terrain.

	Inn	Drava	V.Coast	Po	Rhine	Rhone	Danube
Proglacial systems with identifiable slope threshold (n)	422	86	10	92	300	129	10
Mean	26	24	26	27	27	28	30
Std. dev.	18	18	18	14	18	17	24
Lower quartile	16	13	17	19	18	22	17
Median	25	22	24	27	26	27	27
Upper quartile	32	30	42	32	32	34	35

3.4. Regional associations and patterns

No trend was detected in the slope threshold with east-west or with north-south location across the central European Alps so it is apparently not associated with regional variations such as climate. However, the relationship between slope threshold and hypsometric index identifies two statistically different groups. Specifically, proglacial systems with 'equidimensional' hypsometry have a slope threshold of mean 22.9° that is statistically different to the mean of 25.3° of proglacial systems with 'very bottom heavy' (most area situated at lower elevation) hypsometry. Proglacial systems with bottom heavy hypsometry have a mean slope threshold of 26.4° but the dispersion of the data is sufficiently great for it to belong to both groups, p-value 0.002 (Fig. 9A).

Three statistically different groups exist between hypsometric index and lithology. Proglacial systems underlain by mica schist, magmatite and marlstone all belong to one group in terms of their slope threshold, gneiss and phyllite belong to a second group, and granite belongs to a third group. We note an association of these three groups with grain size, where group 1 rocks are fine/medium-grained, group 2 are medium/coarse-grained, and group 3 has large grains. Statistically, dolomite could belong to either group 2 or 3, p value 0.107 (Fig. 9B).

Analysis of the relationship between slope threshold and lithology identified two groups; one comprising mica schist and phyllite, which are both very well bedded/foliated metamorphic rocks, and one comprising granite, which is a massive igneous rock. Dolomite, limestone, migmatite and gneiss could all statistically belong to either

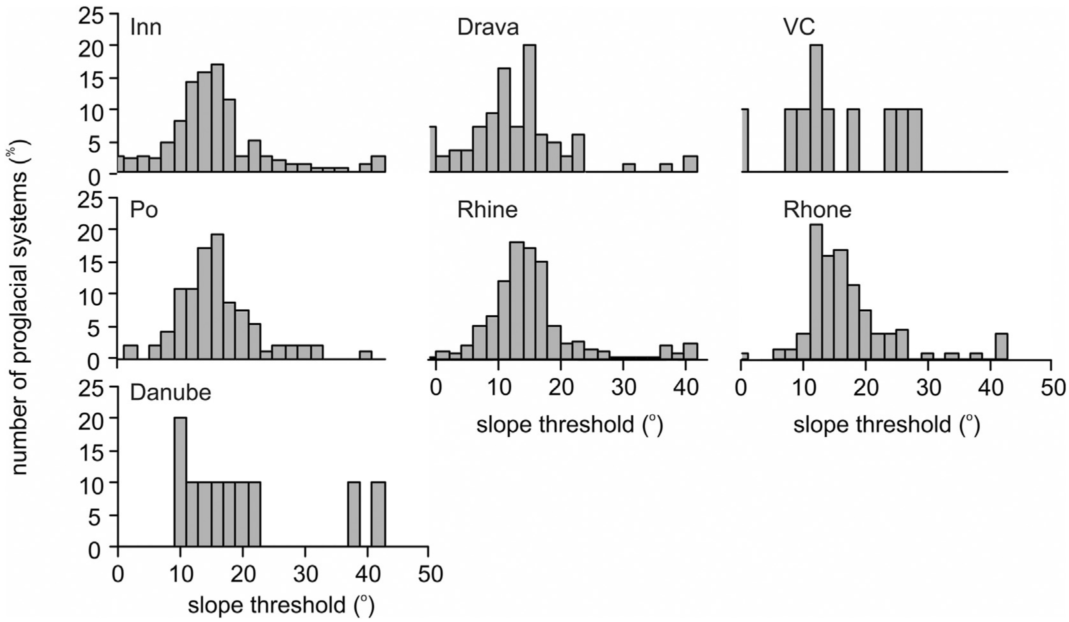

Fig. 6. Histograms of the slope threshold discriminating between fluvial and hillslope-dominated grid cells for proglacial systems in the central European Alps.

group and are either crystalline sedimentary or metamorphic rocks (Fig. 9C). A relationship between rock hardness and the slope threshold discriminating between fluvial and hillslope processes (p-value 0.002) is apparently non-linear and most likely so because phyllite and mica-schist are strongly bedded/foliated and across the central European Alps tend to maintain a high angle of inclination (Fig. 9C).

4. Discussion

On the basis of our definition of proglacial systems being most simply represented by land area between LIA and contemporary glacier margins, we discriminate parts of alpine landscapes that have undergone rapid short term evolution. On the basis of a series of geometric measurements alone it was extremely difficult to identify groupings or patterns in topographic metrics of the proglacial systems of the central European Alps. That was a surprise given that proglacial systems are conventionally assumed to be created or at least primarily conditioned by glaciation (Church and Ryder, 1972) and that those glacial processes are dependent on climate-topography interactions (Raper and Braithwaite, 2009), which vary systematically with location across the European Alps. Nonetheless we were able to spatially characterise geomorphological functioning, landform type, meltwater influence and estimate rates of landscape evolution, all of which are precursors to making informed land and water management across Europe in terms of natural hazards, natural resources, habitat and water quality and ecosystem services, for example.

4.1. Coverage of major geomorphological process domains

We have used a slope threshold value of between 24° and 30° (mean 27°) to quickly discriminate geomorphological functioning; hillslope-dominated (mostly gravitational processes) land surfaces that are steeper than that threshold value, versus fluvially-dominated land surfaces that are shallower than that threshold. Throughout the central European Alps and within most of the proglacial systems that we have analysed it is hillslope-dominated land that covers the greater proportion of proglacial systems. This terrain we interpret to represent gravity-driven falls and slumps rather than fluvially-influenced slides and flows. As an aside we emphasise our use of the word 'dominated'; fluvial processes will occur on slopes steeper than our threshold and hillslope-gravity processes will occur on slopes shallower than our threshold. A predominance of hillslope-dominated land surface(s) implies that greater proportions of proglacial systems are sediment sources and temporary storages, as represented by bedrock cliff falls, debris slumps on talus/scree slopes for example. It follows that the minority of land surface within proglacial systems is fluvially-dominated and therefore comprises major sediment pathways and exports. Our recognition of proglacial systems being hillslope-dominated suggests that that there is an abundant sediment supply, as Maisch et al. (1999) and most recently Schoch et al. (2018) have quantified. Furthermore, these measurements strongly suggest that proglacial systems are most likely to be sediment transport-limited, which has implications for statistical or empirical modelling of sediment transfer (e.g. Bennett et al., 2014; Capt et al., 2016).

4.2. Landforms

Our separation of slope classes identified three statistical boundaries and thus four landform groups. For slopes above the 42° boundary, bedrock is interpreted as a source/generation zone of sediment and also as a landcover that generates instantaneous runoff from rainfall. Talus/scree is the predominant geomorphological entity occupying 26° to 42° slopes and this is a temporary sediment store, initially produced as a paraglacial response soon after deglaciation and destabilisation of surrounding slopes, but then reactivated with additional rockfall (e.g. Kellerer-Pirklbauer et al., 2012), debris flows, intense rainfall, permafrost degradation or undercutting by rivers, for example. Another typical landform contained in this slope interval are steep lateral and terminal moraines (although those can maintain slopes much steeper than 42°, c.f. Lukas et al., 2012). Therefore a slope of 26° is interpreted as a good estimate in general of a slope threshold between sediment entrainment zones or scour as represented in gullies, many of which are fan-head. Debris fall deposits, debris flow deposits and alluvial fans occupy slopes between 26° and 8° and from our widespread field campaigns are apparently zones almost entirely of deposition with volumetrically minor reactivation. Thus they are at least in the short term a sediment sink. Indeed it is coalescing fans that commonly intercalate with valley fill (braided river and floodplain deposits) to submerge many alpine valley floors, as we ourselves have observed in the Ödenwinkelkees, Kaunertal and as Lambiel et al. (2016) map for the Val d'Hérens (Fig. 8).

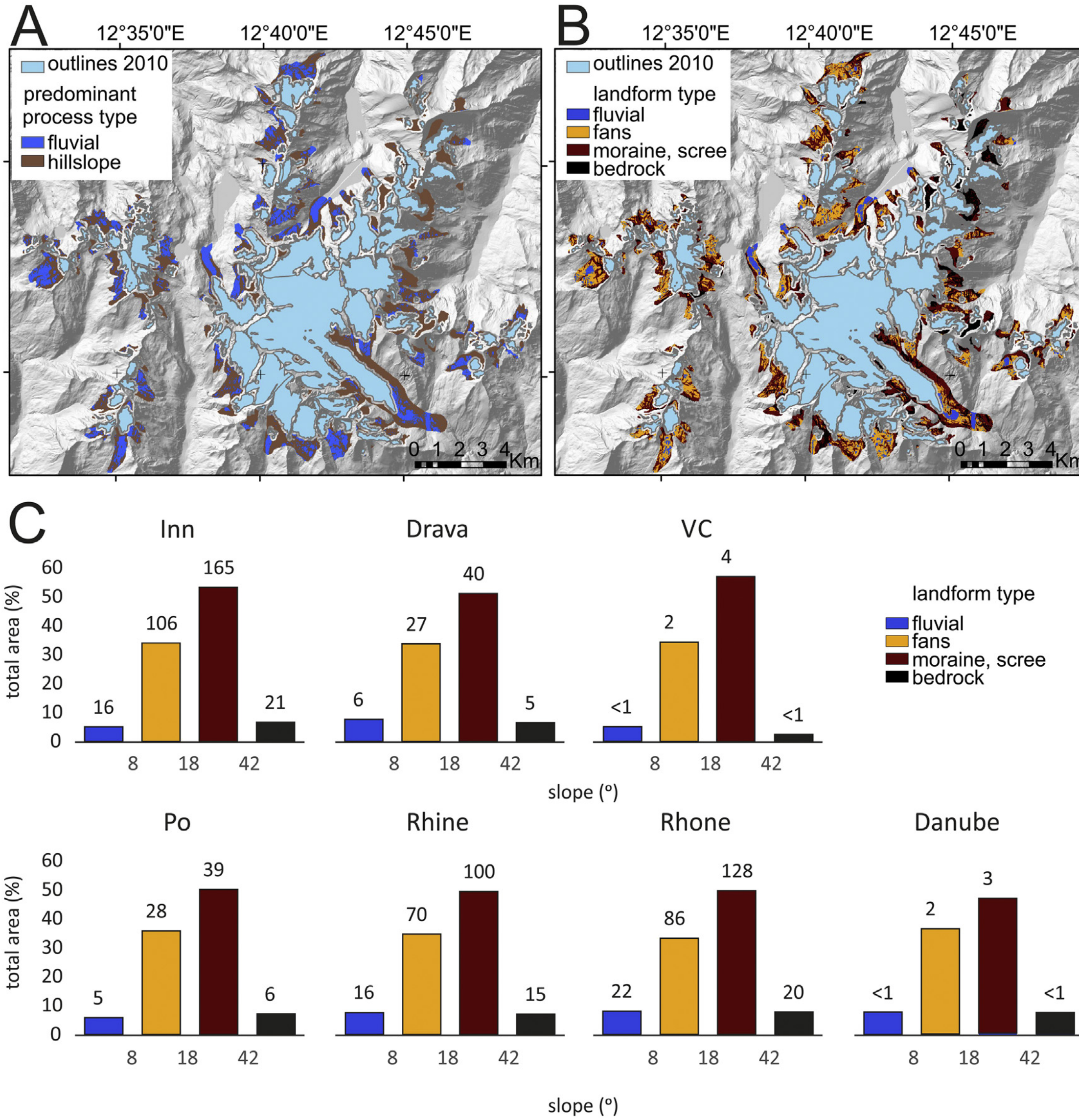

Fig. 7. Results of the slope-contributing area scatterplot analysis to suggest a slope threshold to separate predominant major geomorphological process domains (A), and of PDF analysis on slope values within proglacial systems (A), both displayed in map form for the Gross glockner area of Austria. Relative spatial coverage of each major landform type for each major drainage basin with numbers on top of bars giving absolute area (km^2) (C).

4.3. Water, sediment and solute (WSS) fluxes

WSS sources in proglacial systems comprise glaciers, snow packs, eroding gullies, re-activated fans and river banks. The extremely wide dispersion of values of spatial meltwater influence that we have quantified demonstrates that assumptions of the predominance of glacially-sourced meltwater and fluvially-transported sediment and solute in defining proglacial system character and functioning are rather over-simplifying reality. At least spatially that simplification is apparent, although temporally it is well known that episodic floods can do a lot of geomorphological work (e.g. Warburton, 1990; Staines et al., 2015) despite being restricted to a small proportion of a proglacial system area.

Our analysis has identified likely glacial meltwater pathways and offers an estimate of the spatial coverage, or importance of this meltwater. That spatial importance could be taken as a first-order indication of the sensitivity of a proglacial system to a (future) change in glacial ice meltwater contribution. Such meltwater sensitivity analyses have recently been performed globally, i.e. per major drainage basin, by Huss and Hock (2018) but they report considerable sub-basin (i.e. inter-catchment) variability. In this study we have demonstrated a quick method for quantifying the spatial coverage, or spatial influence, of glacial meltwater and we have shown that varies enormously between proglacial systems within a region and is independent of any recent change in glacier size. We contend that steeper narrower valleys tend to transmit water and sediment beyond a proglacial system, whereas wider shallower valleys tend to permit sediment deposition and progressive aggradation as glaciers diminish. Such spatial analysis and such system sensitivity analysis are both important for understanding intra- and inter-catchment river channel stability, spatio-temporal water temperature regime (Carrivick et al., 2012) and habitat suitability for a wide range of aquatic and riparian organisms (Milner et al., 2017; Fell et al., 2017).

4.4. Landscape evolution

A slope threshold of ~10° was proposed by Palucis et al. (2011) to delimit between debris flow and fluvially-dominated terrain in Meteor Crater. Their value is very much lower than ours for alpine landscapes due to lithology. In the relatively soft (mostly sandstone) sediments of

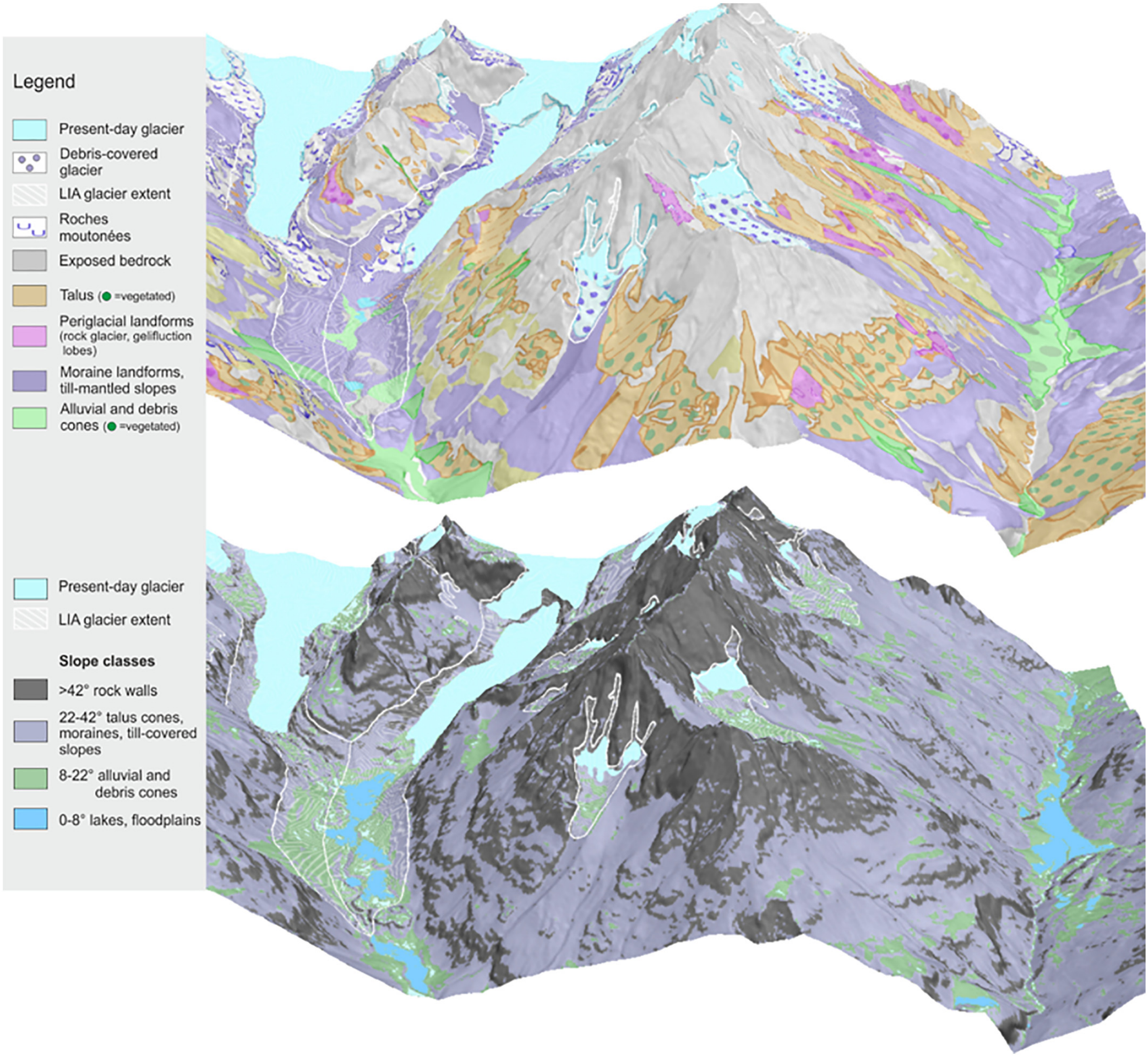

Fig. 8. Three-dimensional perspective visualisation of the Val d'Hérens, Switzerland. The upper part shows a generalised version of a geomorphological map published by Lambiel et al. (2016). The lower panel presents our slope-based classification; the thresholds separating the slope categories were derived from the distribution of slope of the Swiss DEM10 (except present-day glaciers) following Loye et al. (2009), leading to a first-order classification of proglacial systems geomorphology.

Meteor Crater, debris flows cut gullies and fill in troughs, and fluvial processes deliver more sediment and incise the fine-grained material, so that there is a feedback between these debris flow and fluvial processes and both are necessary for landscape evolution. On harder lithologies, with higher tensile strength, such as are typical across the European central Alps, the work of Sklar and Dietrich (2001, 2006) has shown that debris flows will be the primary mechanism by which bedrock incision occurs on steep slopes after deglaciation. This, they report, means that grain size is a key control on bedrock incision and geomorphological work achieved, which seems to be reinforced by our identification of a link between our slope threshold value and our groupings of lithology (Fig. 9). Indeed, grain size control (and rock hardness and sediment supply) has been used to explain scatter that is common in the tail, the fluvial end, of slope-area power law plots (e.g. our Eq. (1)). Landform and landscape evolution is very dependent on sediment supply and there is a critical threshold, which is yet to be ascertained for proglacial systems, whereby too much sediment supply produces land surfaces becoming ‘drowned’, and whereby too little retards abrasion and thus incision. Across the central European Alps Maisch et al. (1999) remarked that sedimentary and mixed sedimentary-rocky glacier beds dominate and so in general sediment supply should be high and valley-fill sediment should persist where topography permits. Valley infill sediments can be detected automatically using low-angle slope filters and as this study has shown major depositional landforms such as alluvial and debris fans can also be discriminated with slope-based analyses.

4.5. Implications for estimating regional proglacial erosion rates

Our maps of meltwater influence, of landforms and of major earth surface processes each offer important information for water and land management, such as characterising (evolving) sediment (and solute)

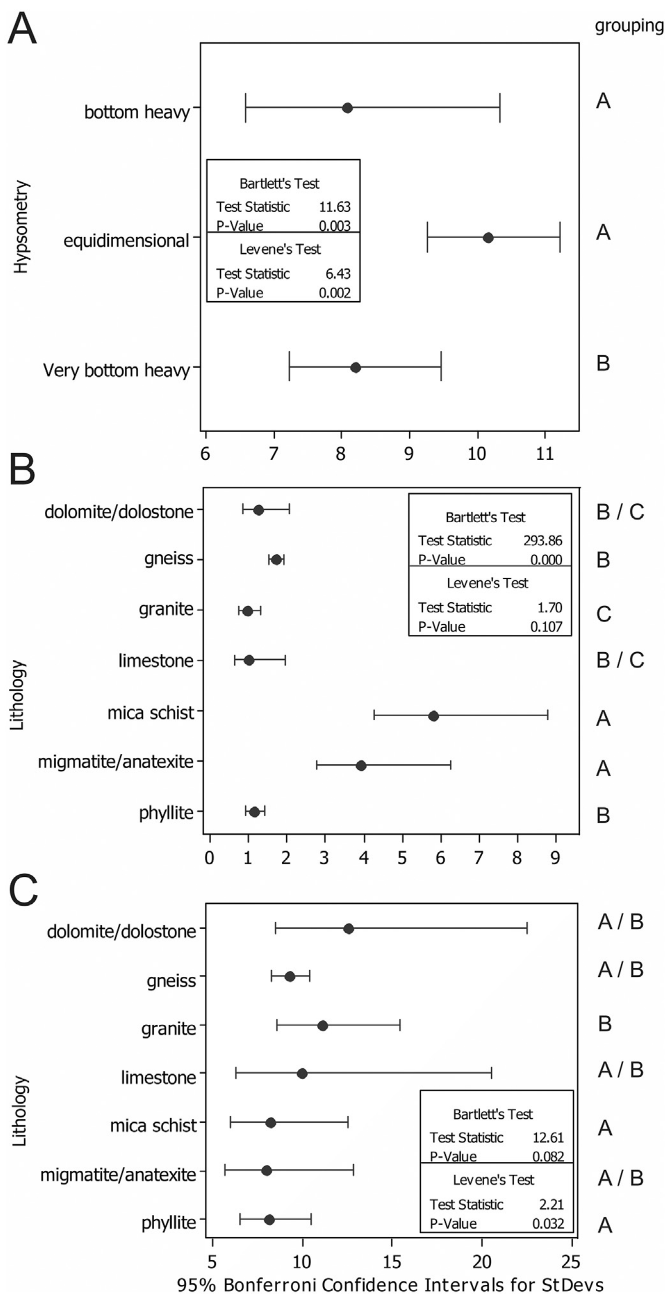

Fig. 9. Test for equal variances and identification of statistical groupings of slope threshold discriminating between hillslope- and fluvially-dominated terrain within proglacial systems of each hypsometric class (A), of hypsometric index with lithology (B), and of slope threshold with lithology (C). Note varying x-scale between panels. Note groupings are not transferable between panels.

sources, pathways and sinks, hillslope and channel stability and thus habitat character and quality. Together these datasets are several of the components necessary to estimate spatially-distributed (inter-catchment) proglacial geomorphology, which can vary markedly between catchments (e.g. Carrivick and Rushmer, 2009), and erosion rates. However, additional data is required on representative erosion rates for different landform classes and as Carrivick and Heckmann (2017; their figure 10) have shown there are very few direct measurements and a very wide range of values, for each landform class. The recent study by Delaney et al. (2018) emphasises problems within a catchment of levels of detection, over-printing (erosion at a point subsequently obscured by deposition), and of converting volume to mass loss (e.g. with debris-covered ice-cored moraine), even with well-constrained annual DEMs spanning >25 years.

To estimate a regional erosion rate, there are problems with applying a relationship from a single proglacial system to all systems because there are many controls on erosion rate other than proglacial area, such as connectivity, area impacted by meltwater etc. Nonetheless, if we assume that the >25 year data reported in Delaney et al.'s (2018). Fig. 3 is representative of proglacial systems (spatially and contemporaneously) across the European Alps a polynomial relationship ($r^2 = 0.96$) can be created between volume change and proglacial area (km^2). Then it is possible to estimate a contemporary total volume loss of 44,003,800 m^3a^{-1} for all central European proglacial systems combined, which equates to a mean of 0.3 $mm \cdot a^{-1}$ contemporary surface lowering. These mean values are a snapshot and an estimate only. They hide the dominant contributions of fewer larger proglacial systems, although 99% of all our estimates were <16 $mm \cdot a^{-1}$. The mean values are greater than the postglacial erosion rates (surface lowering equiv. 0.15 $mm \cdot a^{-1}$) calculated by Campbell and Church (2003) and Hoffmann et al. (2013) for the Coast Mountains of British Columbia, but an order of magnitude less than suggested by single site analyses within the European Alps of geomorphological evidence (e.g. 30 $mm \cdot a^{-1}$ to 90 $mm \cdot a^{-1}$ Curry et al., 2006) and of multi-temporal proglacial DEMs (e.g. 34 $mm \cdot a^{-1}$: Carrivick et al., 2013). They are several orders of magnitude greater than estimates derived from sedimentation within proglacial lakes or reservoirs (as summarised in Carrivick and Heckmann, 2017) which only capture net material efflux rather than intra-catchment mobility. Nonetheless, they probably represent a good estimate of regionally-averaged contemporary rates, especially given that proglacial systems are rapidly expanding and adjusting to climate change through deglaciation, permafrost degradation and meltwater and precipitation regime shifts.

5. Summary and conclusions

We have presented the first quantification of the topography and geomorphological composition of proglacial systems across the central European Alps, and specifically for 2812 sites across Austria and Switzerland. We make these system outlines and distributed elevation data freely available (Carrivick, 2018). We found no association of topographic metrics with location, which we supposed might represent patterns of climatic influence. However, we did find statistically different groups in terms of a relationship between hypsometric index and lithology, and of slope threshold with lithology. Proglacial systems underlain by mica schist, magmatite and marlstone all belong to one group, gneiss and phyllite belong to a second group, and granite belongs to a third group. These relationships suggest that grain size is a key control not only on proglacial system topography but also on the spatial patterning and relative importance of hillslope (mostly gravitational processes) versus fluvial processes and thus on system status as sediment supply- or sediment transport-limited.

For each proglacial system we have defined the spatial coverage of hillslope versus valley-floor fluvial processes and used these to evaluate the spatial arrangement and importance of likely WSS sources, pathways and sinks. Across the central European Alps the proportions of the total proglacial system area belonging to each landform class is remarkably similar, with >5% fluvial, ~35% fans, ~50% moraine ridges and talus/scree, and ~10% bedrock. Identification of the spatial occurrence and importance of these landform classes is very helpful for assessing future earth surface processes and landscape stability, such as via sediment yield and denundation rate calculations, for example, as well as for habitat development because these landforms are the local platform upon which mass movements, soil development and biological activity all react to climate change and human-influenced changes. The spatial association, stability and preservation of these landforms changes perhaps most recognisably in terms of surface connectivity, and as micro-topography and micro-climates permit (e.g. Eichel et al., 2016). As a first-order estimate of the contemporary geomorphological activity and thus landscape evolution represented

by the spatial coverage of these landform classes, we propose a total volume loss from all these proglacial systems equivalent to a mean of 0.3 $m \cdot a^{-1}$ surface lowering.

In conclusion, proglacial systems have become exposed following retreat of glaciers from their LIA margin positions, and have subsequently developed transitioning from glacier-dominated processes to paraglacial processes. Quantifying topographic and geomorphological composition and functioning of proglacial systems is a first and necessary step towards understanding processes driving volume and mass changes within (and exports from) proglacial systems, which themselves are essential for land (stability) and water (quantity and quality) management, hazard analyses and definition of alpine ecosystem services.

We have presented the first regional scale assessment of proglacial system geomorphological composition and functioning and we have done this in a rapid and efficient manner. Our quantitative analysis can be developed towards providing assessments of alpine landscape sensitivity to climate change, most simply start with spatial analyses considering that the most unstable parts of the landscape are where slope is high and soft sediment is present, and the most stable parts are where slopes are low and soft sediment is absent. Future work on landform evolution within proglacial systems could exploit our datasets for determining sediment distribution and sediment supply across proglacial systems (as opposed to from a glacier), and across alpine landscapes, via multivariate geostatistical modelling (Schoch et al., 2018) and via calculation of spatially-distributed (intra-catchment) sediment budget ratios from repeat DEMs (Heckmann and Vericat, 2018), respectively.

Acknowledgement

Rachel Homer is thanked for her advice on statistics.

References

Asch, K., 2003. In: SA 3, BGR, Hannover (Ed.), The 1:5 Million International Geological Map of Europe and Adjacent Areas: Development and Implementation of a GIS-Enabled Concept; Geologisches Jahrbuch. Schweitzerbart, Stuttgart (190 p., 45 fig., 46 tab).

Ballantyne, C.K., 2002. Paraglacial geomorphology. Quat. Sci. Rev. 21, 1935–2017.

Benaglia, T., Chauveau, D., Hunter, D.R., Young, D., 2009. Mixtools: an R package for analyzing finite mixture models. J. Stat. Softw. 32, 1–29.

Bennett, G.L., Molnar, P., McArdell, B.W., Burlando, P., 2014. A probabilistic sediment cascade model of sediment transfer in the Illgraben. Water Resour. Res. 50, 1225–1244.

Beylich, A.A., Laute, K., Storms, J.E., 2017. Contemporary suspended sediment dynamics within two partly glacierized mountain drainage basins in western Norway (Erdalen and Bødalen, inner Nordfjord). Geomorphology 287, 126–143.

Brown, L.E., Dickson, N.E., Carrivick, J.L., Fuereder, L., 2015. Alpine river ecosystem response to glacial and anthropogenic flow pulses. Freshw. Sci. 34, 1201–1215.

Campbell, D., Church, M., 2003. Reconnaissance sediment budgets for Lynn Valley, British Columbia: Holocene and contemporary time scales. Can. J. Earth Sci. 40, 701–713.

Capt, M., Bosson, J.B., Fischer, M., Micheletti, N., Lambiel, C., 2016. Decadal evolution of a very small heavily debris-covered glacier in an Alpine permafrost environment. J. Glaciol. 62, 535–551.

Carrivick, J.L., 2018. Contemporary central European proglacial areas. https://doi.org/10.5518/405.

Carrivick, J.L., Heckmann, T., 2017. Short-term geomorphological evolution of proglacial systems. Geomorphology 287, 3–28.

Carrivick, J.L., Rushmer, E.L., 2009. Inter-and intra-catchment variations in proglacial geomorphology: an example from Franz Josef Glacier and Fox Glacier, New Zealand. Arct. Antarct. Alp. Res. 41, 18–36.

Carrivick, J.L., Tweed, F.S., 2013. Proglacial lakes: character, behaviour and geological importance. Quat. Sci. Rev. 78, 34–52.

Carrivick, J.L., Tweed, F.S., 2016. A global assessment of the societal impacts of glacier outburst floods. Glob. Planet. Chang. 144, 1–16.

Carrivick, J.L., Brown, L.E., Hannah, D.M., Turner, A.G., 2012. Numerical modelling of spatio-temporal thermal heterogeneity in a complex river system. J. Hydrol. 414, 491–502.

Carrivick, J.L., Geilhausen, M., Warburton, J., Dickson, N.E., Carver, S.J., Evans, A.J., Brown, L.E., 2013. Contemporary geomorphological activity throughout the proglacial area of an alpine catchment. Geomorphology 188, 83–95.

Carrivick, J.L., Berry, K., Geilhausen, M., James, W.H., Williams, C., Brown, L.E., Rippin, D.M., Carver, S.J., 2015. Decadal-scale changes of the Ödenwinkelkees, central Austria, suggest increasing control of topography and evolution towards steady state. Geogr. Ann. A 97, 543–562.

Carrivick, J.L., Heckmann, T., Fischer, M., Davies, B., 2018. An inventory of proglacial systems in Austria, Switzerland and across Patagonia. In: Heckmann, T., Morche, D. (Eds.), Geomorphology of Proglacial Systems. Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes. Springer International Publishing (accepted for publication).

Church, M., Ryder, J.M., 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. Geol. Soc. Am. Bull. 83, 3059–3072.

Curry, A.M., Cleasby, V., Zukowskyj, P., 2006. Paraglacial response of steep, sediment-mantled slopes to post-'Little Ice Age' glacier recession in the central Swiss Alps. J. Quat. Sci. 21, 211–225.

Daten Österreichs, 2016. Digitales Geländemodell (DGM) Österreich. https://www.data.gv.at/katalog/dataset/b5de6975-417b-4320-afdb-eb2a9e2a1dbf (Last visited March, 2016).

Delaney, I., Bauder, A., Huss, M., Weidmann, Y., 2018. Proglacial erosion rates and processes in a glacierized catchment in the Swiss Alps. Earth Surf. Process. Landf. 43, 765–778.

Dickson, N.E., Carrivick, J.L., Brown, L.E., 2012. Flow regulation alters alpine river thermal regimes. J. Hydrol. 464, 505–516.

EEA, 2009. Regional climate change and adaptation — the Alps facing the challenge of changing water resources. https://www.eea.europa.eu/publications/alps-climate-change-and-adaptation-2009 (last visited February 2018).

Eichel, J., Corenblit, D., Dikau, R., 2016. Conditions for feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes: a biogeomorphic feedback window. Earth Surf. Process. Landf. 41, 406–419.

Fell, S.C., Carrivick, J.L., Brown, L.E., 2017. The multitrophic effects of climate change and glacier retreat in mountain rivers. Bioscience 67, 897–911.

Fischer, M., Huss, M., Barboux, C., Hoelzle, M., 2014. The new Swiss Glacier Inventory SGI2010: relevance of using high-resolution source data in areas dominated by very small glaciers. Arct. Antarct. Alp. Res. 46, 933–945.

Fischer, A., Seiser, B., Stocker-Waldhuber, M., Abermann, J., 2015. The Austrian Glacier Inventory GI 3, 2006, in ArcGIS (Shapefile) Format. https://doi.org/10.1594/PANGAEA.844985.

Fischer, M., Huss, M., Hoelzle, M., 2015. Surface elevation and mass changes of all Swiss glaciers 1980–2010. Cryosphere 9, 525–540.

Glaziologie Österreich, 2016. Österreichische Gletscherinventare (GI). http://www.glaziologie.at/gletscherinventar.html (Last visited March, 2016).

Groß, G., Patzelt, G., 2015. The Austrian Glacier Inventory for the Little Ice Age Maximum (GI LIA) in ArcGIS (Shapefile) Format. https://doi.org/10.1594/PANGAEA.844987.

Heckmann, T., Morche, D. (Eds.), 2018. Geomorphology of Proglacial Systems; Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes. Springer International Publishing (in press).

Heckmann, T., Vericat, D., 2018. Computing spatially distributed sediment delivery ratios: inferring functional sediment connectivity from repeat high-resolution Digital Elevation Models. Earth Surf. Process. Landf. 43, 1547–1554.

Heckmann, T., McColl, S., Morche, D., 2016a. Retreating ice: research in pro-glacial areas matters. Earth Surf. Process. Landf. 41, 271–276.

Heckmann, T., Hilger, L., Vehling, L., Becht, M., 2016b. Integrating field measurements, a geomorphological map and stochastic modelling to estimate the spatially distributed rockfall sediment budget of the Upper Kaunertal, Austrian Central Alps. Geomorphology 260, 16–31.

Hoffmann, T., Müller, T., Johnson, E.A., Martin, Y.E., 2013. Postglacial adjustment of steep, low-order drainage basins, Canadian Rocky Mountains. J. Geophys. Res. Earth Surf. 118, 2568–2584.

Huss, M., 2011. Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. Water Resour. Res. 47, W07511.

Huss, M., Hock, R., 2018. Global-scale hydrological response to future glacier mass loss. Nat. Clim. Chang. 8, 135–142.

IGME, 2016. International Geological Map of Europe. http://www.bgr.de/karten/IGME5000/igme5000.htm (last visited October 2016).

Jiskoot, H., Curran, C.J., Tessler, D.L., Shenton, L.R., 2009. Changes in Clemenceau Icefield and Chaba Group glaciers, Canada, related to hypsometry, tributary detachment, length–slope and area–aspect relations. Ann. Glaciol. 50, 133–143.

Kellerer-Pirklbauer, A., Lieb, G.K., Avian, M., Carrivick, J.L., 2012. Climate change and rock fall events in high mountain areas: numerous and extensive rock falls in 2007 at Mittlerer Burgstall, Central Austria. Geogr. Ann. A 94, 59–78.

Kociuba, W., 2017. Assessment of sediment sources throughout the proglacial area of a small Arctic catchment based on high-resolution digital elevation models. Geomorphology 287, 73–89.

Lambiel, C., Maillard, B., Kummert, M., Reynard, E., 2016. Geomorphology of the Hérens valley (Swiss Alps). J. Maps 12, 160–172.

Lane, S.N., Bakker, M., Gabbud, C., Micheletti, N., Saugy, J.N., 2017. Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. Geomorphology 277, 210–227.

Litschauer, 2014. Save the alpine rivers! http://www.ecrr.org/Portals/27/Events/ERRC2014/Presentations/28%20october%202014/session6/STAR_ERRC_2014.pdf (last visited February 2018).

Loye, A., Jaboyedoff, M., Pedrazzini, A., 2009. Identification of potential rockfall source areas at a regional scale using a DEM-based geomorphometric analysis. Nat. Hazards Earth Syst. Sci. 9, 1643–1653.

Lukas, S., Graf, A., Coray, S., Schlüchter, C., 2012. Genesis, stability and preservation potential of large lateral moraines of Alpine valley glaciers–towards a unifying theory based on Findelengletscher, Switzerland. Quat. Sci. Rev. 38, 27–48.

Maisch, M., 2000. The long-term signal of climate change in the Swiss Alps: glacier retreat since the end of the Little Ice Age and future ice decay scenarios. Geogr. Fis. Din. Quat. 23, 139–151.

Maisch, M., Haeberli, W., Hoelzle, M., Wenzel, J., 1999. Occurrence of rocky and sedimentary glacier beds in the Swiss Alps as estimated from glacier-inventory data. Ann. Glaciol. 28, 231–235.

Micheletti, N., Lane, S.N., 2016. Water yield and sediment export in small, partially glaciated Alpine watersheds in a warming climate. Water Resour. Res. 52, 4924–4943.

Milner, A.M., Khamis, K., Battin, T.J., Brittain, J.E., Barrand, N.E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G.M., Jacobsen, D., Hannah, D.M., Hodson, A.J., 2017. Glacier shrinkage driving global changes in downstream systems. Proc. Natl. Acad. Sci. 114, 9770–9778.

Palucis, M., Dietrich, W., Howard, A., 2011. The role of debris flows in the origin and evolution of gully systems on crater walls: martian analogs in meteor crater, Arizona (USA). Ital. J. Eng. Geol. Environ. 2011, 243–252. https://doi.org/10.4408/IJEGE.2011-03.B-029.

Raper, S.C., Braithwaite, R.J., 2009. Glacier volume response time and its links to climate and topography based on a conceptual model of glacier hypsometry. The Cryosphere 3 (2), 183–194.

Schoch, A., Blöthe, J.H., Hoffmann, T., Schrott, L., 2018. Multivariate geostatistical modeling of the spatial sediment distribution in a large scale drainage basin, Upper Rhone, Switzerland. Geomorphology 303, 375–392.

Sklar, L.S., Dietrich, W.E., 2001. Sediment and rock strength controls on river incision into bedrock. Geology 29, 1087–1090.

Sklar, L.S., Dietrich, W.E., 2006. The role of sediment in controlling steady-state bedrock channel slope: implications of the saltation–abrasion incision model. Geomorphology 82, 58–83.

Staines, K.E., Carrivick, J.L., Tweed, F.S., Evans, A.J., Russell, A.J., Jóhannesson, T., Roberts, M., 2015. A multi-dimensional analysis of pro-glacial landscape change at Sólheimajökull, southern Iceland. Earth Surf. Process. Landf. 40, 809–822.

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resour. Res. 33, 309–319.

TauDEM, 2016. TauDEM Documentation. Utah State University. http://hydrology.usu.edu/taudem/taudem5/documentation.html, Accessed date: October 2017.

Warburton, J., 1990. An alpine proglacial fluvial sediment budget. Geogr. Ann. A 72 (3-4), 261–272.